CLOUD PARAMETER RETRIEVAL FROM MIPAS DATA

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ABSTRACT

Clouds are a source of major uncertainty in climate models - it is thus important to accurately model clouds in order to determine their properties. In this work, three cloud parameters (cloud top height, cloud top temperature and cloud extinction coefficient) are used to model the radiance measured in the MIPAS field-of-view as they represent the most obvious physical, thermodynamic and optical properties, respectively, of a cloud. Finally, this model is implemented in an optimal estimations-type retrieval of cloud top height, temperature and extinction coefficient from real MIPAS spectra.

Key words: cloud; MIPAS; retrieval.

1. INTRODUCTION

Previous work (Hurley [3])give quick, easy and to a first order, reasonable estimates of cloud top height. However, it is an oversimplification to assume that all clouds encountered will be thermodynamically black, having infinite extinction and characterised by a single brightness temperature throughout their entire extent. It is reasonable to expect that thick clouds will be characterised by a single brightness temperature - however, thinner clouds clearly have some non-constant temperature structure.

MIPAS is an infrared limb-sounding Michelson interferometer onboard the ENVISAT satellite which was launched in March 2002. If the Earth is viewed side-on, the atmosphere appears as a halo around it - this halo is known as the limb. MIPAS measures using limb emission, which is a technique consisting of looking through the limb with cold space as a background and measuring the infrared radiation thermally emitted in the atmosphere along the line of sight. Limb sounders are particularly good at observing cloud because they have inherently good vertical resolution and the long horizontal limb path gives a more substantial area over which to measure trace gases.(Allen [1])

This work desribes how to model non-scattering clouds, having finite cloud top height (CTH), cloud top temperature (CTT) and temperature structure, and cloud extinction coefficient (k_{ext}). It will attempt to model clouds with extinction coefficients in the range of 0.001 km^{-1} to 0.1 km^{-1} since below this scattering is likely to be important and above this the cloud becomes black and becomes well modelled by any extinction coefficient greater than about 0.1 km^{-1}. Finally, this model is implemented in an optimal estimations-type retrieval of CTH, CTT and k_{ext} from real MIPAS spectra.

2. FORWARD MODEL: RADIANCE IN THE MIPAS FOV

The radiance emitted by a cloud in the field of view (FOV) of width $2d$ can be simply modelled as

$$R_C = \frac{\int_{-d}^{z_{filled}} L(z)\phi(z)dz}{\int_{-d}^{d} \phi(z)dz} \tag{1}$$

where L(z) is the radiance emitted at tangent point z within the FOV by the cloud and $\phi(z)$ is the FOV convolution. Furthermore, L(z) can be expanded as

$$L(z) = \int B(z)d\tau \tag{2}$$

for the Planck function $B(z)$ and transmission τ. By definition,

$$\tau = e^{-k_{ext}\xi} \tag{3}$$

where ξ is the total pathlength, and so it follows that

$$d\tau = k_{ext}e^{-k_{ext}\xi}. \tag{4}$$

Fig. 1 shows a schematic of the system.

So the total pathlength is

$$\xi = x + x_{ct}, \tag{5}$$

whereby x_{ct} represents the pathlength from the cloud top to a tangent point and x represents the pathlength from a point within the cloud to the tangent point. It follows then, that

$$L(z) = k_{ext}\int_{-x_{ct}(z)}^{x_{ct}(z)} B(z')e^{-k_{ext}(x(z')+x_{ct}(z))}dx. \tag{6}$$

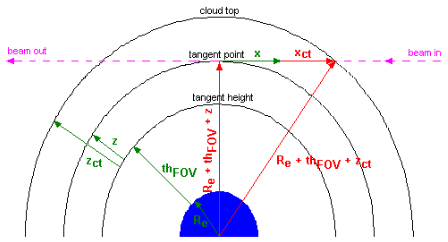

Figure 1. Schematic of the viewing geometry of MIPAS with a cloud in the FOV.

Let's simplify our notation and say that for a beam passing through z_i in the FOV, that the radiance emitted along the ith path is

$$L_i = k_{ext} \int_{-x_{ct_i}}^{x_{ct_i}} B(z) e^{-k_{ext}(x(z)+x_{ct_i})} dx. \quad (7)$$

Simple geometry gives that

$$(R_e + th_{FOV} + z_i)^2 + x_{ct_i}^2 = (R_e + th_{FOV} + z_{ct})^2, \quad (8)$$

which expands to

$$x_{ct_i} = \sqrt{(R_e + th_{FOV} + z_{ct})^2 - (R_e + th_{FOV} + z_i)^2}. \quad (9)$$

Now, the temperature is not constant along the path traced through the cloud by each beam at z_i. Rather, at a distance x from the tangent point at z_i, the temperature is

$$T_x = T_i + \Gamma_{wet}(z_x - (R_e + th_{FOV} + z_i)), \quad (10)$$

where T_i is $T(z_i)$, $\Gamma_{wet} = -6.0$ K/km is the wet adiabatic lapse rate and z_x is the altitude at x.

The vertical offset is

$$\Delta z = \frac{x^2}{2(R_e + th_{FOV} + z_i)}, \quad (11)$$

and thus

$$T_x = T_i + \Gamma_{wet} \Delta z. \quad (12)$$

It should be noted that $T_x < T_i$ always since $\Delta z > 0$.

Changing from continuous to discrete notation,

$$L_i = k_{ext} \sum_{j=0(-x_{ct_i})}^{(x_{ct_i})} B(T_j) e^{-k_{ext}(x_j + x_{ct_i})} \Delta x_j \quad (13)$$

for

$$T_j = T_i + \Gamma_{wet} \Delta z_i \quad (14)$$

and

$$\Delta z_i = \frac{x^2}{2(R_e + th_{FOV} + z_i)}. \quad (15)$$

The total radiation emitted within the FOV is then

$$R_C = \frac{\sum_{i=0(-d)}^{(z_{ct})} L_i \phi_i}{\sum_{i=0(-d)}^{(d)} \phi_i}. \quad (16)$$

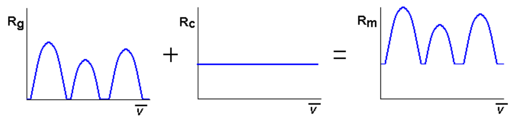

Figure 2. Schematic of the radiance contributions in a cloudy FOV.

2.1. Gas Correction

For non-black clouds, there is significant signal captured by the MIPAS spectra which is due to the atmospheric emissions and absorptions, and so the total measured radiance cannot necessarily be considered to be coming from the cloud in the instrument FOV. The measured radiance R_m can be expressed as

$$R_m = x_1 R_g + x_2 R_c \quad (17)$$

where R_g is the radiance contributed by the constituent atmospheric gases, R_c is the radiance emitted by the cloud, and (x_1,x_2) are constant coefficients. The gaseous radiance contribution is expected to have emission/absorption lines whereas the cloudy contribution will be a nearly continuum signal as shown schematically in Fig. 2.

Using a simple retrieval method, **y** = **Kx**, we can take **y** to be the measured spectrum (R_m), $\mathbf{x} = (x_1, x_2)$ to be the coefficients and **K** = (R_g, R_c) to be the forward model. The inverse problem requires then that

$$\mathbf{x} = (\mathbf{K}^T \mathbf{K})^{-1} \mathbf{K}^T \mathbf{y} \quad (18)$$

and if R_c is taken to be uniformly equal to 1 nW/cm^2 sr cm^{-1} across the wavenumber range of interest, it follows that x_2 is equal to the radiance emitted by the cloud alone in the FOV.

2.2. Implementation and Validation

The 960.0 cm^{-1} to 961.0 cm^{-1} microwindow is again used to model and retrieve cloud parameters. In order to retrieve three cloud parameters (CTH, CTT and k_{ext}) with greater certainty, two measurements will be used. Since two consequetive sweeps in the lower altitude range in the MIPAS scan pattern essentially see the same part of the atmosphere, as highlighted for the nominal scan pattern in Fig. 3, the two measurements will be the mean radiance in the chosen microwindow from two adjacent sweeps. The radiance emitted is modelled in the FOV in which the cloud top height first occurs ("upper FOV", at a tangent height of th_c) and the FOV immediately below ("lower FOV", with a tangent height of th_b).

Using the model previously described with the gas correction, the radiance emitted within the FOV for cloud

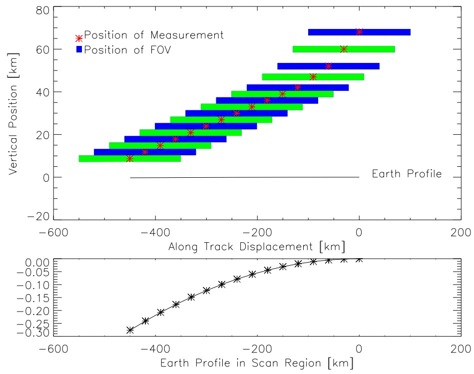

Figure 3. The relative locations of the field-of-views in the MIPAS nominal scan pattern. For the lower sweeps in the scan pattern, clearly two adjacent sweeps measure nearly the same portion of the atmosphere.

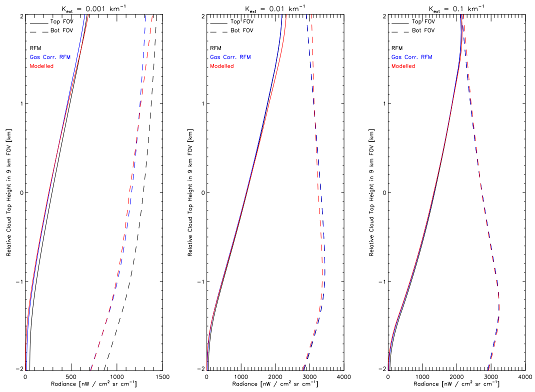

Figure 4. Radiance emitted in a partially-filled-cloudy FOV as the cloud top height is moved upwards through the 4 *km-wide FOV. Clearly, the model and gas correction work perfectly if the red and blue lines overlay each other.*

top heights located at every 100 m throughout the 4 km-wide FOV with k_{ext} equalling 0.1 km^{-1}, 0.01 km^{-1} and 0.001 km^{-1} was calculated. The model was validated by comparison with RFM-simulated cloud banks of known cloud top height and extinction coefficient (Dudhia [2]). Fig. 4 shows the comparison of the radiance emitted by the cloud (R_c) as the cloud top height is moved upwards through the FOV (tangent height of FOV corresponds to a relative cloud top height within the FOV of 0 km) for extinction coefficients of 0.1 km^{-1}, 0.01 km^{-1} and 0.001 km^{-1}. Clearly the model and gas correction work quite well.

3. SEQUENTIAL RETRIEVAL

Three cloud parameters (cloud top height CTH, cloud top temperature CTT and cloud extinction coefficient k_{ext}) are of interest because they describe the most obvious

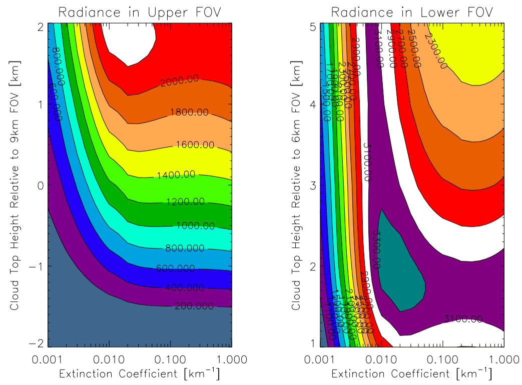

Figure 5. Radiance measured in the upper and lower fields-of-view, where cloud is first encountered. Here the cloud top is given in kilometers above a 9 *km tangent height.*

physical, thermodynamic and optical features, respectively, of the cloud. Using the forward model described in the previous sections, an optimal estimation-type retrieval (OER) will be employed in an attempt to retrieve the three parameters.

3.1. *A Priori* Dependence

Cloud modelling is a highly non-linear process, even when considered on the vastly simplified scale. Essentially, given a pair of radiances from two adjacent sweeps in a scan pattern, there can be two possible clouds present: a high thin cloud, or a low thick cloud, as highlighted in Fig. 5. Depending upon which *a priori* is supplied to an OER, equally valid different solutions will result.

3.2. Adding Information by Effective Fraction

If one proposes to use only two measurements to retrieve three parameters, there will always be a set of possible solutions, unless another piece of information is added. There are several potential places to look for more information, however the most convenient is to use a cloud detection mechanism (such as the Colour Index Method, Spang [4]) in which the detecting quantity is strongly related to the cloud effective fraction (EF). It is well known that the present CI Method has several caveats and has not been optimized, but nevertheless it exhibits a relation to EF that can be empirically dervied at the very least.

Cloud effective fraction (EF) is defined as

$$EF = \frac{\int_{-d}^{z_{ct}} (1 - e^{-k_{ext} x}) \phi(z) dz}{\int_{-d}^{d} \phi(z) dz} \quad (19)$$

for a FOV of width $2d$ characterised by convolution function $\phi(z)$ - it is essentially the effective blocking power

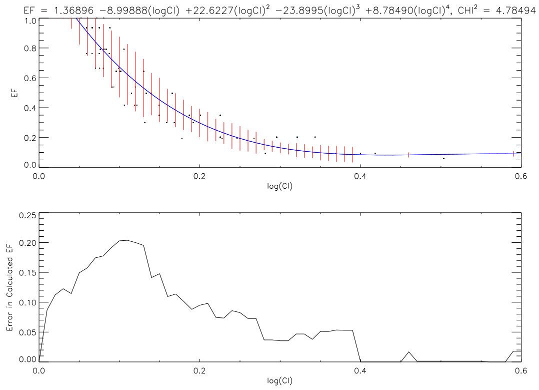

Figure 6. Relation between cloud effective fraction and colour index for RFM-simulated clouds in the MIPAS A band as defined by the present microwindows. In the top panel the black asterixes represent the RFM simulated clouds, the blue line the fit of EF vs. CI, with errors given in red. In the bottom panel, given a value of CI, the error in the calculated EF is estimated.

of the cloud within the FOV - the proportion of the FOV filled by cloud multiplied by the absorption of the cloud.

A useful (and eventual) exercise would be to optimise the microwindows used in the CI definition, so that there is maximum correlation between cloud effective fraction and CI - however, for the moment, the current microwindows will be used. Using three different extinction coefficients (0.001 km^{-1}, 0.01 km^{-1} and 0.1 km^{-1}), four standard RFM atmospheres (day, polar summer, polar winter and tropical) and nine different cloud top heights at a tangent height of 9 km, for a total of 108 different cloudy atmospheric conditions, the radiance ratio for present CI microwindows was calculated, as shown in Fig. 6. It was found that the basic functional form that best fitted the ratio was

$$EF = c_0 + c_1 logCI + c_2 (logCI)^2 + c_3 (logCI)^3 + c_4 (logCI)^4 \quad (20)$$

for real constants c_0, c_1, c_2, c_3 and c_4. Although it may be that this relationship will not be applicable for other pairs of microwindows, and in particular may not represent the optimal relationship between EF and CI, this form is used to estimate the EF from CI.

3.3. Retrieval Scheme

Using both the radiance information and the effective fraction information, one can successfully retrieve cloud top height (CTH), cloud top temperature (CTT) and cloud extinction coefficient (k_{ext}) through a sequential retrieval, as schematically represented in Fig. 7.

By the detection method used to identify cloudy spectra, the CI for retrieval candidates will be known and thus the EF can easily be estimated for the cloudy field-of-view.

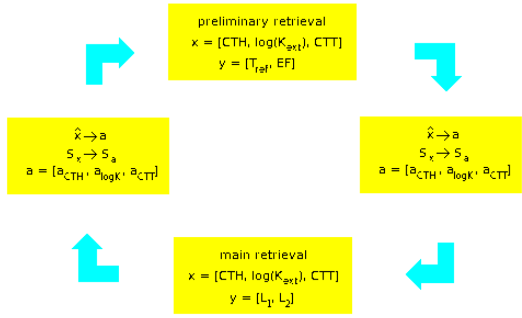

Figure 7. Schematic of sequential retrieval scheme. The preliminary retrieval uses the retrieved temperature of the cloudy FOV and effective fraction as pseudo-measurements to estimate the state vector. The main retrieval uses the radiance measurements from the first FOV flagged as cloudy and those of the FOV immediately below.

The idea is to add information by using this derived EF in order to better characterise the *a priori*, especially in terms of extinction, so that the retrieval is closer to the correct cost minima to begin with. However, it is again not a simple issue of simply solving for k_{ext} from EF, as any given EF can be obtained by varying the cloud top height and extinction of the cloud. Thus, it is necessary to carry out a preliminary retrieval to first get an appropriate guess of the state vector which will be used as the *a priori* in the main radiance retrieval.

Basically, the sequential retrieval consists of two separate retrievals (“preliminary” and “main”) which independently use difference pieces of information in an attempt to retrieve the state vector (CTH, log(k_{ext}),and CTT) and then feed their results back and forth until a converged set of values is reached.

The preliminary retrieval uses the retrieved temperature of the first field-of-view flagged as cloudy (T$_{ret}$) and cloud effective fraction EF as derived from the Colour Index (CI) as pseudo-measurements

$$\mathbf{y} = \begin{pmatrix} T_{ret} \\ EF \end{pmatrix} \quad (21)$$

and retrieves the state vector

$$\mathbf{x} = \begin{pmatrix} CTH \\ log(k_{ext} \\ CTT \end{pmatrix}. \quad (22)$$

The main retrieval uses the same state vector, and two radiance measurements such that

$$\mathbf{y} = \begin{pmatrix} L_c \\ L_b \end{pmatrix}. \quad (23)$$

Both the preliminary and main retrievals use the one-step optimal estimation formulation of

$$\hat{\mathbf{x}} = \mathbf{a} + \mathbf{S}_x \mathbf{K}^T \mathbf{S}_y^{-1} (\mathbf{y} - \mathbf{F}) \quad (24)$$

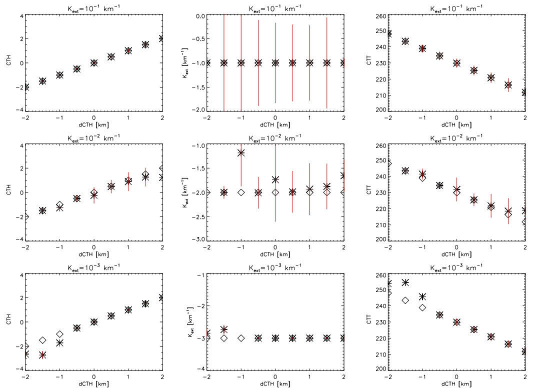

Figure 8. Results of sequential retrieval applied to RFM simulated data, showing “true” (diamonds) and retrieved (asterisks plus red error bars) values for the three parameters (vertical axis) as a function of position of cloud top relative to centre of the FOV (horizontal axis) and different log(k_{ext}), (different rows of plots - thick cloud in top row, thin cloud in bottom row).

where $\mathbf{S}_x$ is the error convariance matrix, **K** is the Jacobian, $\mathbf{S}_y$ is the measurement error covariance matrix and **F** is the appropriate forward model.

The sequential retrieval begins by using the Colour Index Method to identify the first sweep in a scan pattern which contains cloud. Then the linearisation point for the preliminary retrieval in the first iteration of the sequential retrieva; is determined and the sequential proceeds by passing each new retrieved state vector and covariance matrix to the next retrieval as *a priori* until convergence is reached.

3.4. Validation with RFM Simulations

The sequential retrieval has been applied to and validated with RFM simulations for cloudy FOVs with known CTH, CTT and k_{ext}. Three values of extinction have been simulated (0.001 km^{-1}, 0.01 km^{-1} and 0.1 km^{-1}) and nine cloud top heights within a FOV at 9.0 km, with their corresponding cloud top temperatures determined by the temperature profile at the cloud top height. Fig. 8 shows the success of the sequential retrieval at accurately determining the three cloud parameters for thick to thin clouds. There is reasonable agreement for nearly all of the retrieved values, except for those having very small EFs (less than 1%), as encountered for $k_{ext} = 0.001$ km^{-1} having $CTH < -1.5$ km below the tangent height of the FOV.

4. APPLICATION TO MIPAS DATA

The sequential retrieval scheme has been run on a 2003 MIPAS level 1C spectra sampled one day out of every

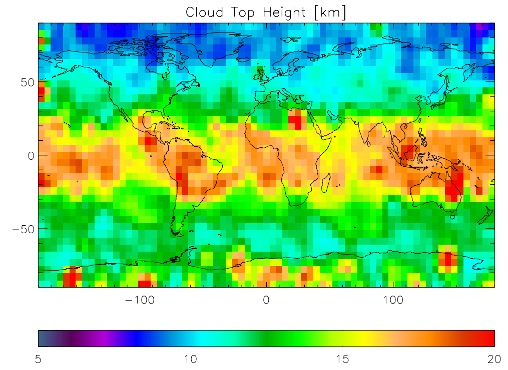

Figure 9. Retrieved cloud top height for MIPAS 2003.

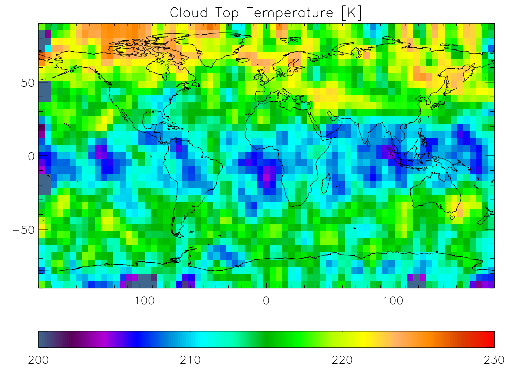

Figure 10. Retrieved cloud top temperature for MIPAS 2003.

ten. The retrieved values of CTH, CTT and log(k_{ext}) have been averaged in 5^o by 5^o latitude-longitude bins for the full year-long period of study. The resulting maps of high cloud CTH, CTT and extinction (Fig. 9, 10, 11) exhibit some reassuring behaviour, namely:

- “Hot spot” of high cloud over Indonesian toga core;
- Occurrence of high cloud over mountainous regions such as the Southern Andes and Rockies;
- Increased high cloud over Amazon Basin and the Congo;
- Increasing cloud top height towards the tropics;
- Retrieved cloud top temperature is nearly fully anti-correlated with cloud top height;
- Retrieved log(k_{ext}) is more or less constant ove rthe globe, however this is probably a result of picking the highest cloud only in the MIPAS scan to analyze.

The time series for the zonally averaged-values of CTH, CTT and log(k_{ext}) are shown in Fig. 12 for the full year. There are several trends to note:

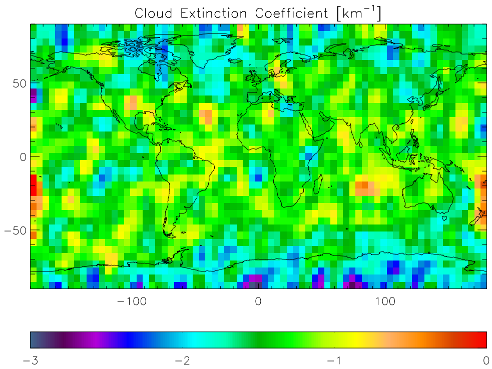

Figure 11. Retrieved cloud top extinction for MIPAS 2003.

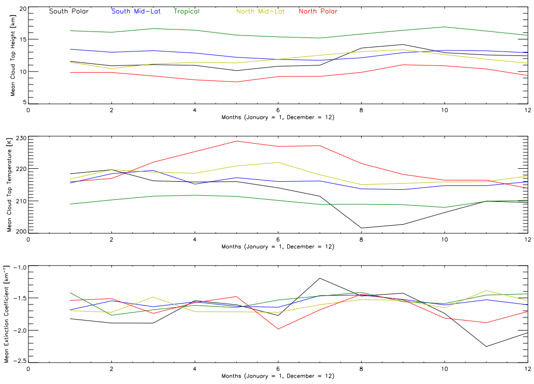

Figure 12. Time series for CTH (top), CTT (middle) and log(k_{ext}) (bottom) for the full year of 2003 from MIPAS.

- Cloud Top Height:
  - The lowest zonal values are encountered in the corresponding winter seasons;
  - The highest zonal values are encountered in the corresponding summer seasons;
  - The highest clouds seen over the southern polar region occur in September/October with the return of light (probably are polar stratospheric clouds);
- Cloud Top Temperature:
  - Basically fully anti-correlated with cloud top height;
- Cloud Extinction Coefficient:
  - The thinnest clouds appear to occur over the poles.

5. DISCUSSION

This preliminary study confirms that cloud top height, cloud top temperature and extinction coefficient can be successfully retrieved by modelling clouds quite simply and using a sequential optimal estimations-type retrieval whereby an estimate for cloud effective fraction initiates the retrieval close to the correct cost minimum. This retrieval method has then been successfully applied to a year's worth of MIPAS level 1C spectra to produce global maps of cloud top height, cloud top temperature and cloud extinction coeficient which compare well with well-known cloud climatologies.

ACKNOWLEDGMENTS

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